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NRL Memorandum Report 1147

AN ADVANCED SPACE SURVEILLANCE SYSTEM
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ABSTRACT

Requirements for a space surveillance system are now being generated by the various unified and specified commands. While details remain to be determined, in general it may be stated that the requirements express a need for three categories of coverage: (a) early detection, (b) coverage of low inclinations, and (c) coverage at extreme altitudes.

A minimum-cost, space surveillance system which provides early orbit determination of all satellites out to nearly 30,000 nautical miles is described. The system consists of U.S. installations, to provide refined orbital data on most known satellites, and special installations, to provide data on orbital elements of new satellites and special orbits. The special installations would be located on islands in the Pacific and Caribbean to provide extended longitude coverage and to provide equatorial coverage for both low-period and 24-hour-period orbits.

The detection device described utilizes high-powered, continuous-wave transmitters, fixed antennas, a nonambiguous ranging technique, and precise determination of angles to give a good orbit (error in period approx. 0.1%) for satellites above 350 nautical miles (seen by two stations) and a less accurate orbit for satellites below that altitude seen by one station (error in period 0.1% to 1%).

The proposed initial installation at Truk-Ponape and in Florida provides 30,000-mile coverage for the island installation and lower latitude coverage for the U.S. experimental installation.

PROBLEM STATUS

This is a proposal for extension of the Space Surveillance System. Work is continuing on the approved program.

AUTHORIZATION

R02-35

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AN ADVANCED SPACE SURVEILLANCE SYSTEM

INTRODUCTION

Background

The U.S. Naval Research Laboratory initiated a system development in June 1958, designed to detect and predict orbits on nonradiating satellites. The program was sponsored by the Advanced Research Projects Agency under Order 7 until October 18, 1960, whereupon administrative and technical responsibility was transferred to the Department of the Navy. NORAD is responsible for providing requirements, representing the needs of all services, which are to be the basis for a development plan.

The present Naval Space Surveillance System measures angles, angular rates, and doppler. Satellite positions are determined by simultaneous angular measurements. The use of angular rates and doppler provides a crude orbital determination from one pass. The use of positions determined on two passes provides a good orbital determination.

This system was adapted to a continental U.S. location and is not compatible with installation on restricted areas such as an island. For early detection of satellites, an island installation will be necessary. The detection system to be described in this proposal is an extension of the present system, is compatible with an island installation, and is designed to satisfy the anticipated military requirements.

Requirements

The requirements, now in preparation, are known in broad terms and indicate a need for: (a) coverage of all orbit inclinations, (b) extending the range to detect satellites of military interest, (c) providing detection of low satellites, (d) early detection of unannounced satellites, (e) provision of timely output information, and (f) suitability for wartime operations. This last item includes high reliability and freedom from interference. The range of detection has no finite limit. There is always a tradeoff between range, assumed reflecting area, and probability of detection. A special, and useful, satellite is one approximating a 24-hour period, stationary orbit. Such satellites would be located at about 22,000 nautical miles from the earth. A requirement for coverage to include such satellites is assumed.

System Concept

The present Naval Space Surveillance System has employed techniques selected primarily to solve the problem of detecting orbiting objects. Simplicity, low cost, and high reliability have been important considerations.

Radio illumination from the ground provides the means of "seeing" nonradiating satellites. Because the returned signal varies with the inverse fourth power of the range, and because ranges are extremely great, it is important to maintain a

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high average transmitter power. A pulse system may employ pulse compression and signal processing to increase the average power. A continuous-wave (cw) system reaches the optimum in this respect and, in addition, is simple, reliable, and permits the use of narrowband receivers for high sensitivity. Therefore, cw illumination has been selected.

A thin vertical-fence type of coverage has been selected. This is practical because of the inability of satellites to make radical and frequent changes in their orbit. The observations are made at the point of closest approach to maximize the range capability. The thin beam reduces the possibility of multiple satellites passing simultaneously through the system. Also, there is no scanning loss. High-gain antennas must be employed to make long-range detection practical. Rows of dipoles above a horizontal ground screen are used for most arrays.

Narrow predetection and postdetection bandwidths are used in the receivers. The postdetection bandwidths are chosen to match the signal duration. These will be automatically selected in systems covering both short and long ranges. Narrow predetection bandwidths are obtained by use of a comb filter, which finds the doppler-shifted frequency and tunes the measuring system to the proper frequency so that a narrow bandwidth may be employed.

The observational data are taken with a radio-interferometer system. Such a system permits very high angular resolution with simple antenna design. The resolution is dependent upon the separation of a pair of antennas. Separations of one mile are to be used.

For installations on limited property, such as an island, range as well as angular measurements would be made. Range is provided by employing what might be termed a frequency interferometer. A side frequency, removed, say, a few hundred cycles from the primary illuminator frequency and locked in phase with it, is transmitted. The phase difference between the received frequencies when compared to the directly received transmission is a measure of the range. Because the side frequency is fixed in frequency relative to the primary detection frequency, knowledge of where to look can be provided by the detection channel, thereby minimizing the required side frequency power. Use of several side frequencies increases the accuracy in ranging and eliminates ambiguities.

The principal problem with a cw detection system is the need for eliminating feedthrough from transmitter to receiver. This problem is reduced by separating the transmitter by a good distance from the receiver. A minimum distance of approximately thirty miles is indicated. Further isolation is obtained by the use of suitable antenna patterns and filtering.

Early Detection

Figure 1 shows the approximate, initial, subsatellite tracks for Russian satellites launched to date. As shown, the first pass that crosses the U.S. is #6. To detect pass #1 a station on Johnston Island is indicated. However, if the period

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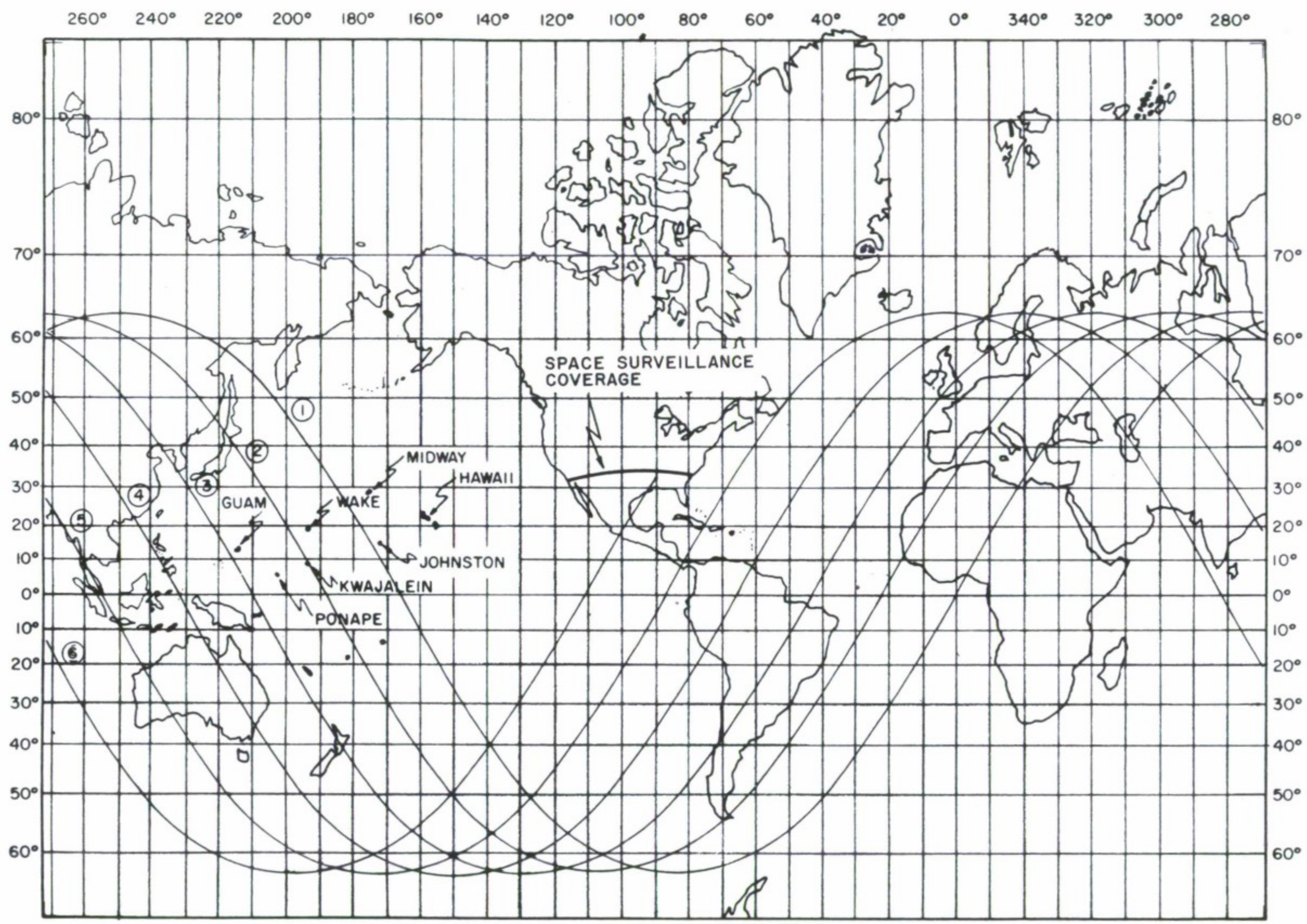

Fig. 1 - Approximate, initial, subsatellite tracks for Russian satellites to date

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of the orbit is long and the launching site is west of the spot shown this pass might be missed. In the case of a miss, the first detection will still occur over the U.S. A station in the area of Ponape would, at worst, detect the second orbit and might detect the first orbit.

The longitude coverage that can be obtained from a single site is limited by the minimum height of the satellite to be detected. For detection to 85 nautical miles, the earth's curvature limits the detection range to 750 nautical miles. This coverage from Truk-Ponape is shown in Fig. 2.

The longitude of Ponape is approximately 90° from the center of the present line and is thereby in the optimum position to minimize the detection time (for a single installation) for the general case of any satellite having an inclination above 33°. Thus, Ponape is an attractive location for an initial extension of the present system.

The addition of stations in the region of the Philippines, Hawaii, the U.S., and Puerto Rico would provide nearly 100 percent first-orbit coverage for satellites having inclinations greater than about 10°. For lower inclinations, an installation looking south from the Philippine will detect every orbit (Fig. 3).

The Pacific Missile Range has communications to Hawaii, Kwajalein, Guam, and the Philippines and proposed communications to Tarawa (Fig. 4). The Army has the additional communications shown.

High-Altitude Coverage

The coverage of satellites at extreme altitudes is complicated by their extrem range and by the characteristic (for 24-hour satellites) of not necessarily crossin many degrees of longitude. The subsatellite tracks of 24-hour satellites may be a point (for a circular, zero-inclination orbit). For a zero-inclination, non-circul orbit, the track will cover a path along the equator. For different inclinations and eccentricities the orbits will describe tracks which resemble figure 8's of various distortions.

Since such satellites can continuously survey any particular section of the earth's surface (except near the poles), they are of particular interest for reconnaissance devices. For detecting all such devices, a minimum of three stations would be required to cover the entire equatorial plane throughout the range of interest.

Size of Objects

In designing a detection system one of the first parameters that must be selected is that of effective target size. In the Navy Space Surveillance System the measured variations in size of several satellites have been determined and are shown in Fig. 5. These curves show that the plot of size (σ) versus the probability of a given size being exceeded is a log normal distribution.

The distribution shown in Fig. 6 has been chosen for calculation purposes. Here, a one-square-meter object is defined as one which appears to be one square

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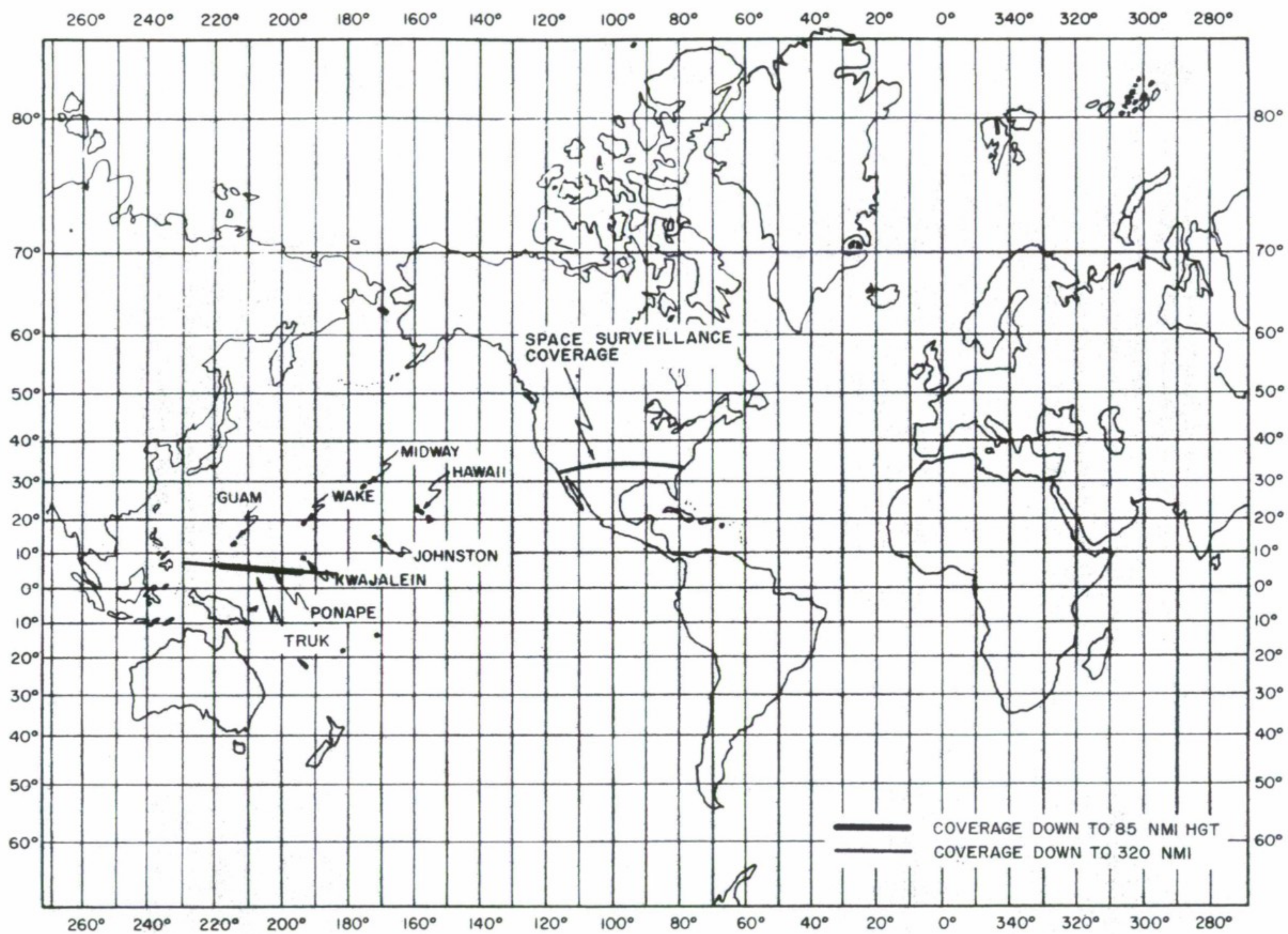

Fig. 2 - Detection coverage of the Truk-Ponape installation

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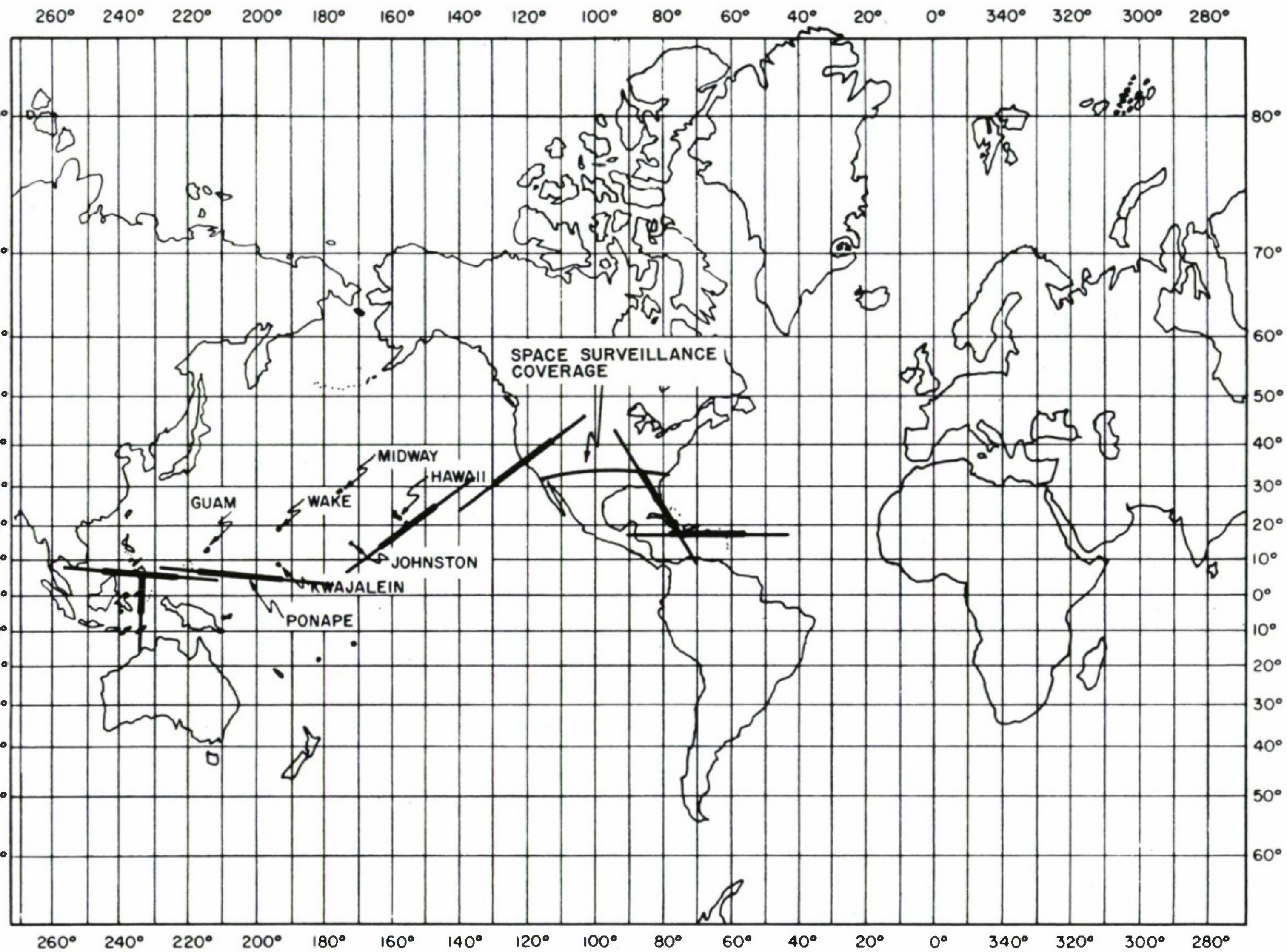

Fig. 3 - Complete space surveillance system with 180^0 longitudinal coverage and equatorial coverage

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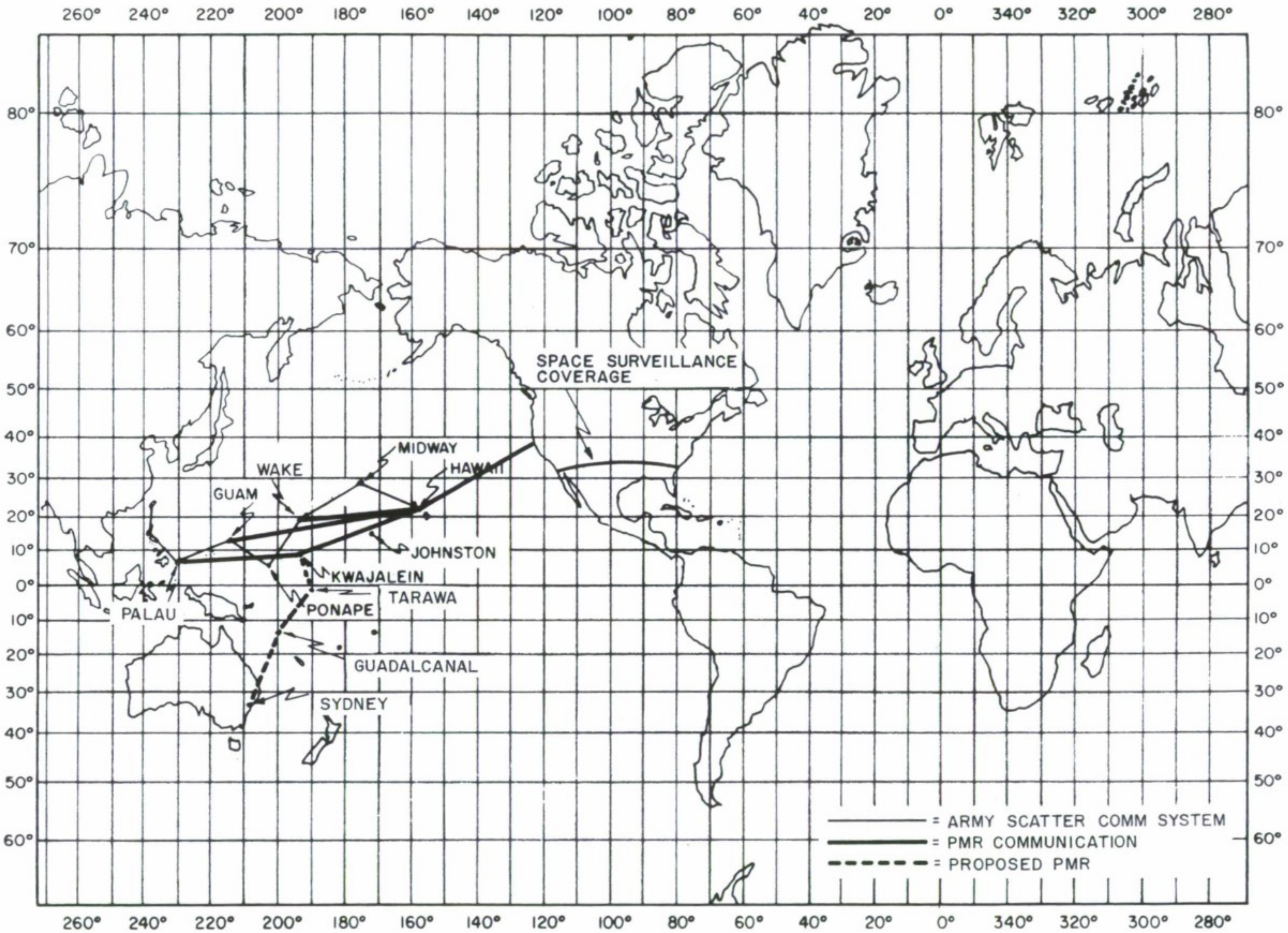

Fig. 4 - Some existing communication systems in the Pacific

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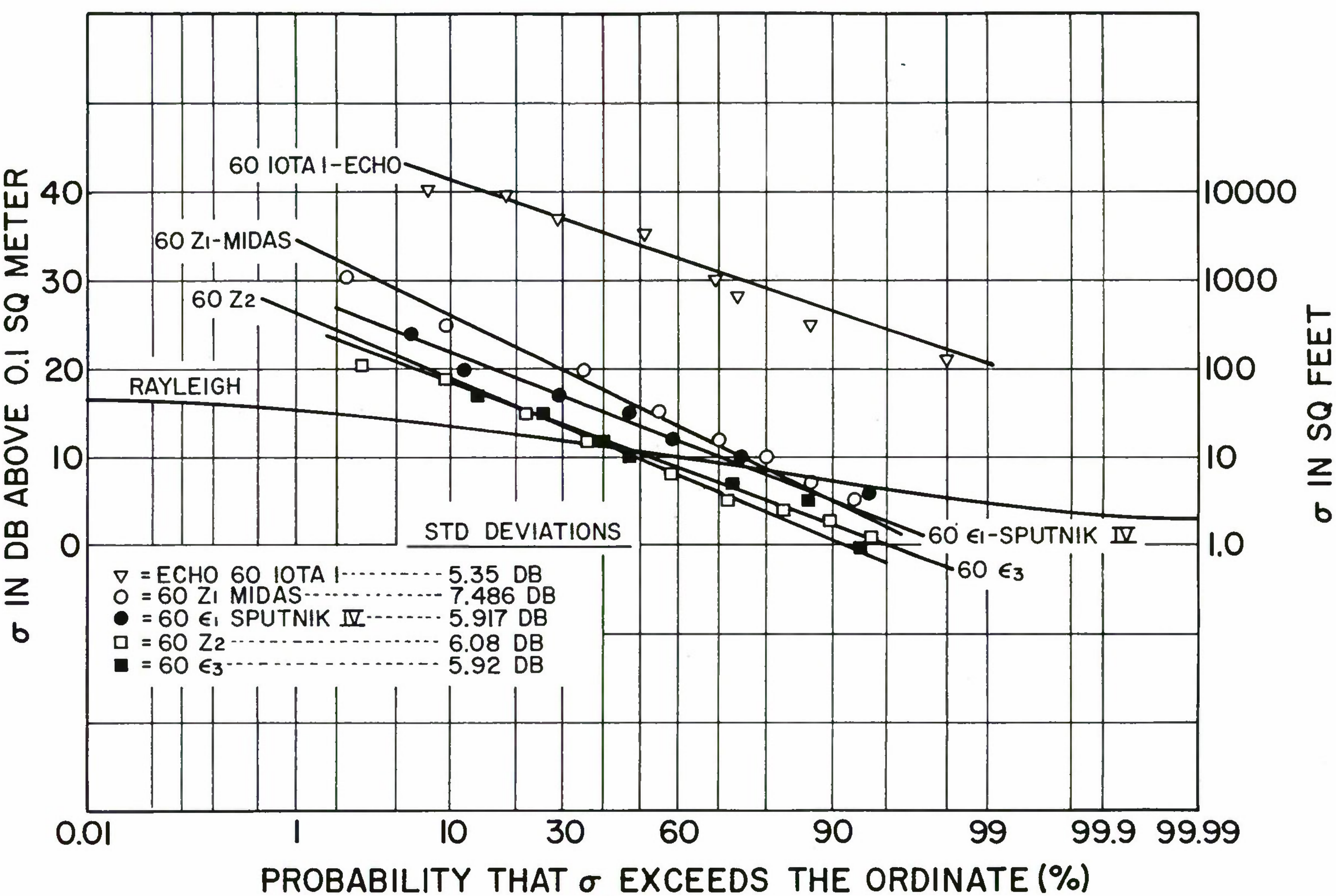

Fig. 5 - Actual satellite size and the probability that in measuring, the size of the measurement exceeds the corresponding ordinate value

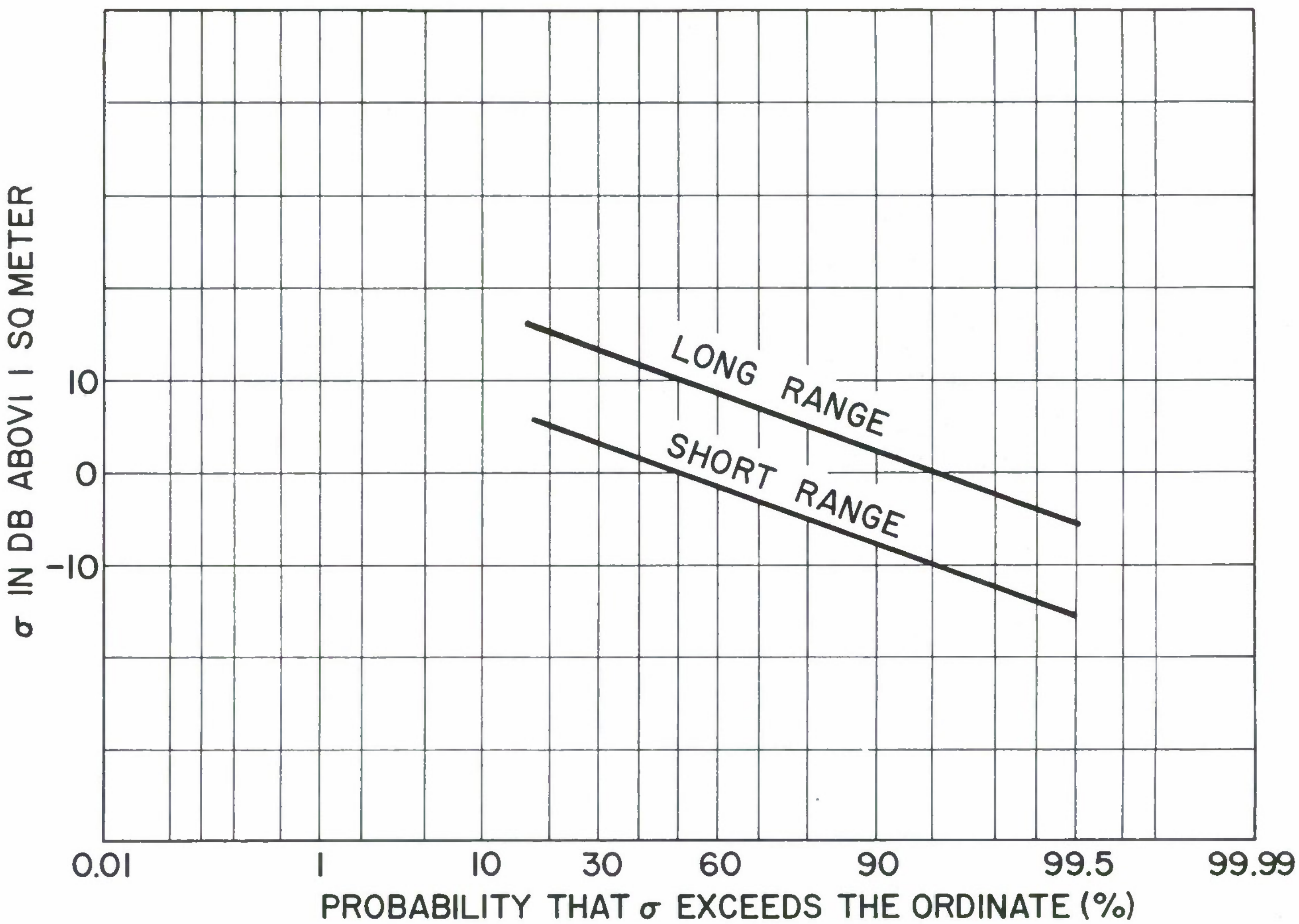

Fig. 6 - Assumed satellite sizes and the probability that in measuring, the size of the measurement exceeds the corresponding ordinate value

meter or larger for 50 percent of the observations, and from the figure it is seen that for 95 percent of the observations it will appear to be larger than 0.1 square meter. To compute the range of a system having a 95 percent probability of detection on a one-square-meter target, a size of 0.1 m^2 is used in the radar equation. In the detection system to be described, a 0.1 m^2 target size is used in the calculation for close satellites (under 4000 nautical miles) and 1 m^2 for targets at great distances (4000 to 30,000 nautical miles) giving, in each case, a 95 percent probability of detection for satellites ten times as large.

SYSTEM DESIGN

Detection of Distant Objects (4000 to 30,000 naut mi)

The first system described is designed for detection at extreme ranges. It may be easily degraded for use at any lesser range. It is assumed that detection of this object will be accomplished by means of a radio reflecting system, which is limited in range according to the well known equation

$$R^4 = \frac{P_t}{P_r} \frac{G_1 G_2 \lambda^2 \sigma}{(4\pi)^3} .$$

From this equation it is obvious that for detection at great ranges the transmitted power must be large, the antennas must have high gains, and the receivers must be sensitive.

The transmitted-power parameter that determines range in an optimized system is the energy, or average power, multiplied by observation time. The most efficient means of generating such energy (high average power) is by the use of a continuous-wave transmitter.

High-gain antennas can be produced economically only if they are fixed devices. Since the function of the antennas is to illuminate the equatorial plane, fan-type beams are indicated. Such beams can be produced by antennas which are both economical and rugged.

The requirement for a sensitive receiver affects the choice of frequency of operation. Low-noise receivers are easily built at the lower frequencies, and at these frequencies (approx. 100 Mc/s) the system sensitivity is determined by sky noise. The doppler band also is less, so fewer filters need be used in the comb preselector. The optimum detection frequency for a system using fan-type antennas is in the region of roughly 150 to 500 Mc/s.

Calculation of Range

The range is calculated on the basis of a transmitter of 2 mw and an antenna 2 miles long. The receiving antennas are 1 mile long. Calculations are made for both 150 and 450 Mc/s.

The sensitivity of the system is determined by one of two possible controlling factors. One factor is the detection sensitivity of the system, and the other is the sensitivity of the phase-measurement equipment. For detection sensitivity the signal required to attain a signal-to-noise ratio of 13 db in a given filter band is first determined.

Consider Fig. 7 for the case of a postdetection bandwidth (B) of 0.2 cycle and a predetection bandwidth (b) of 100 cycles. The sensitivity is 153 dbm. Now consider Fig. 8 for the same postdetection bandwidth and a predetection bandwidth of 25 cps and a phase noise (ϕ_n) of 25°. At a post detection bandwidth of 1 cycle the sensitivity is 156 dbm. At B = 0.2 it would be 163 dbm. By making the detection antenna at least 7 db more sensitivity then the phase-measuring system, the phase-measuring device becomes the controlling factor.

At 450 Mc/s the procedure is the same, except the bandwidth is greater, and since the temperature is less the sensitivity is 6 db greater than for the 1000°K curves shown. To keep the number of filters constant, the bandwidth at 450 Mc/s is assumed to be 300 cycles, as contrasted to 100 cycles at 150 Mc/s. Under these conditions, as shown in Table 1, the range obtained at the two frequencies is identical. A schematic of the range coverage is shown in Fig. 9.

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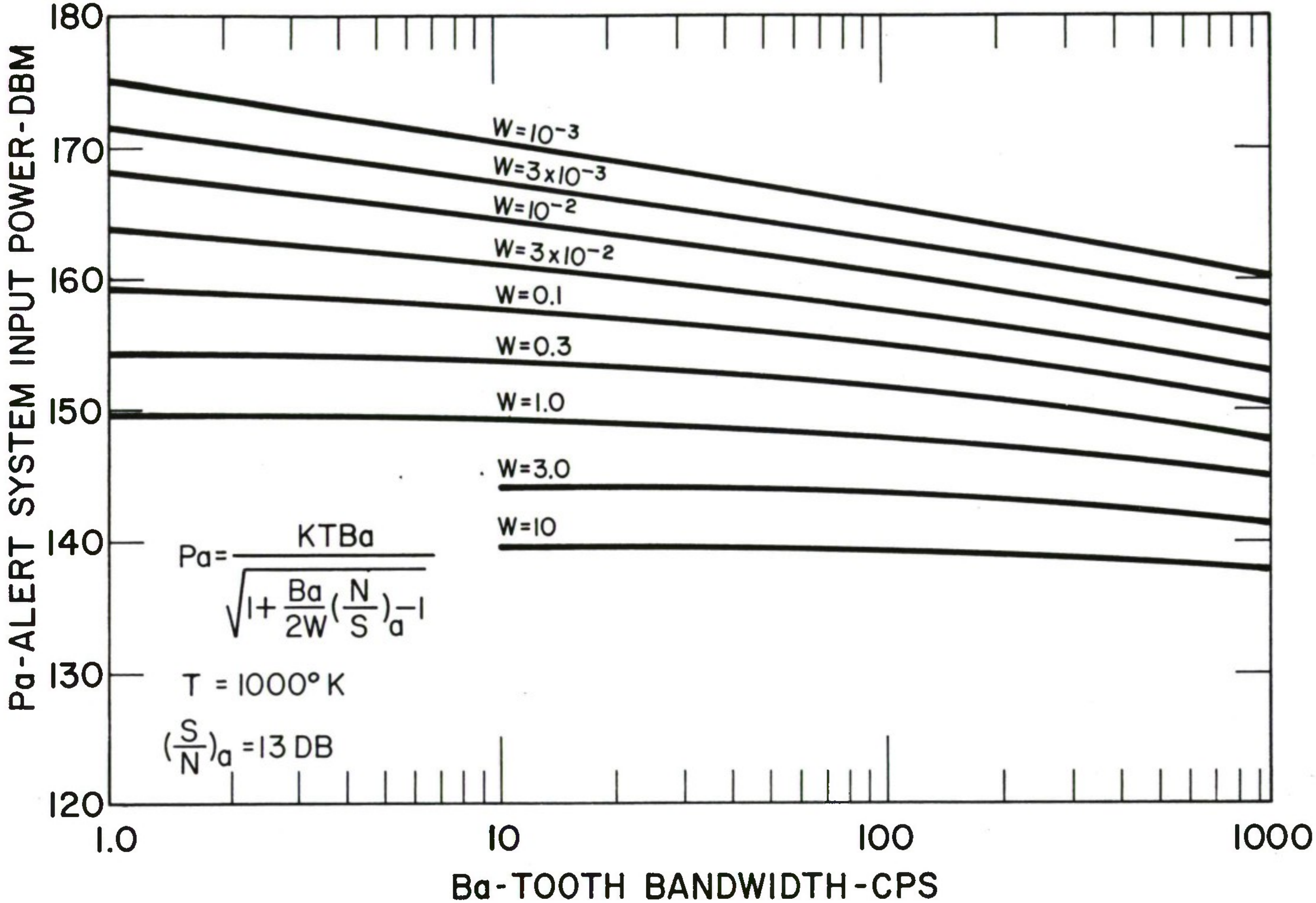

Fig. 7 - Alert-system sensitivity (input power vs predetection bandwidth)

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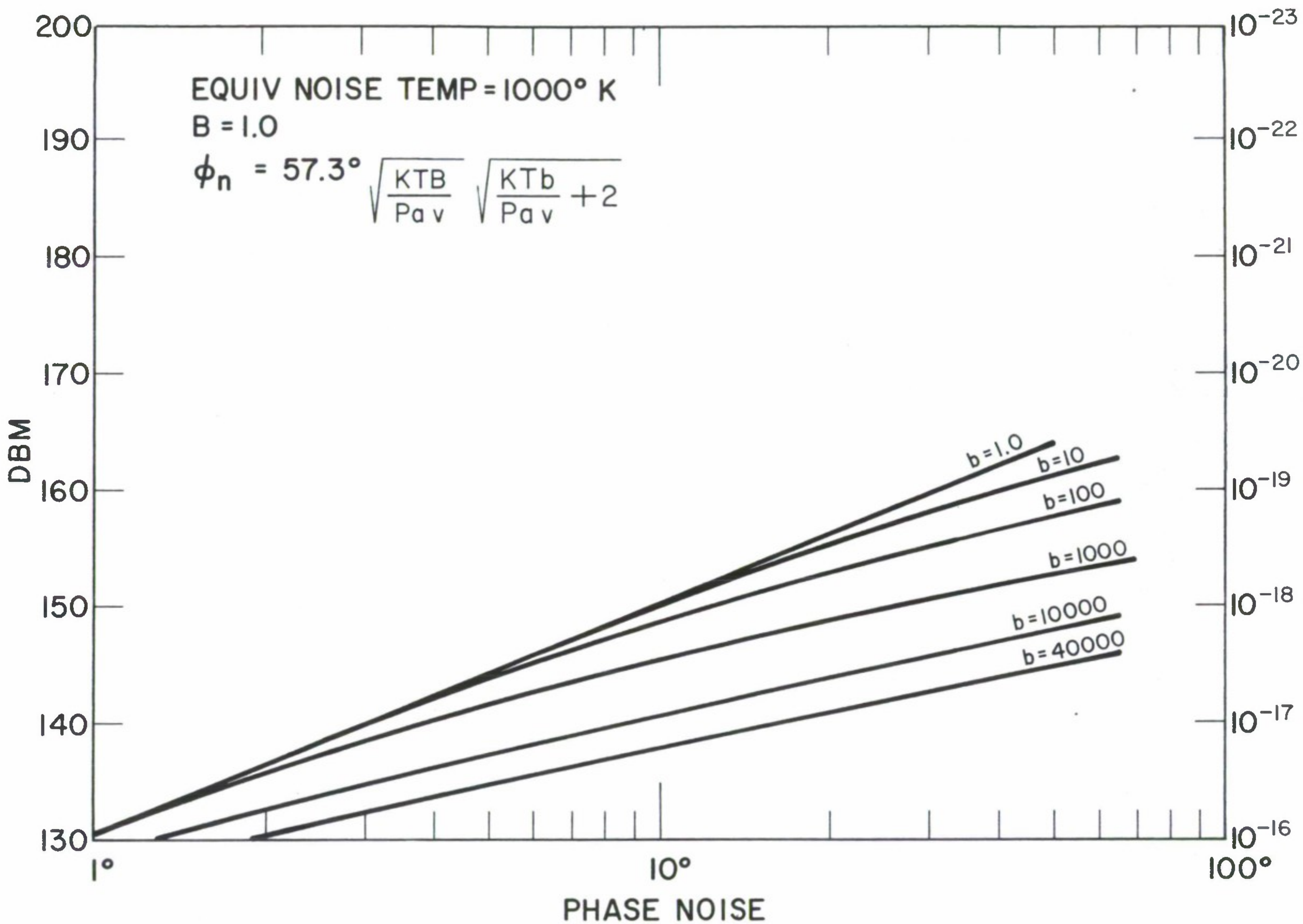

Fig. 8 - Phase-meter sensitivity (input power vs phase noise)

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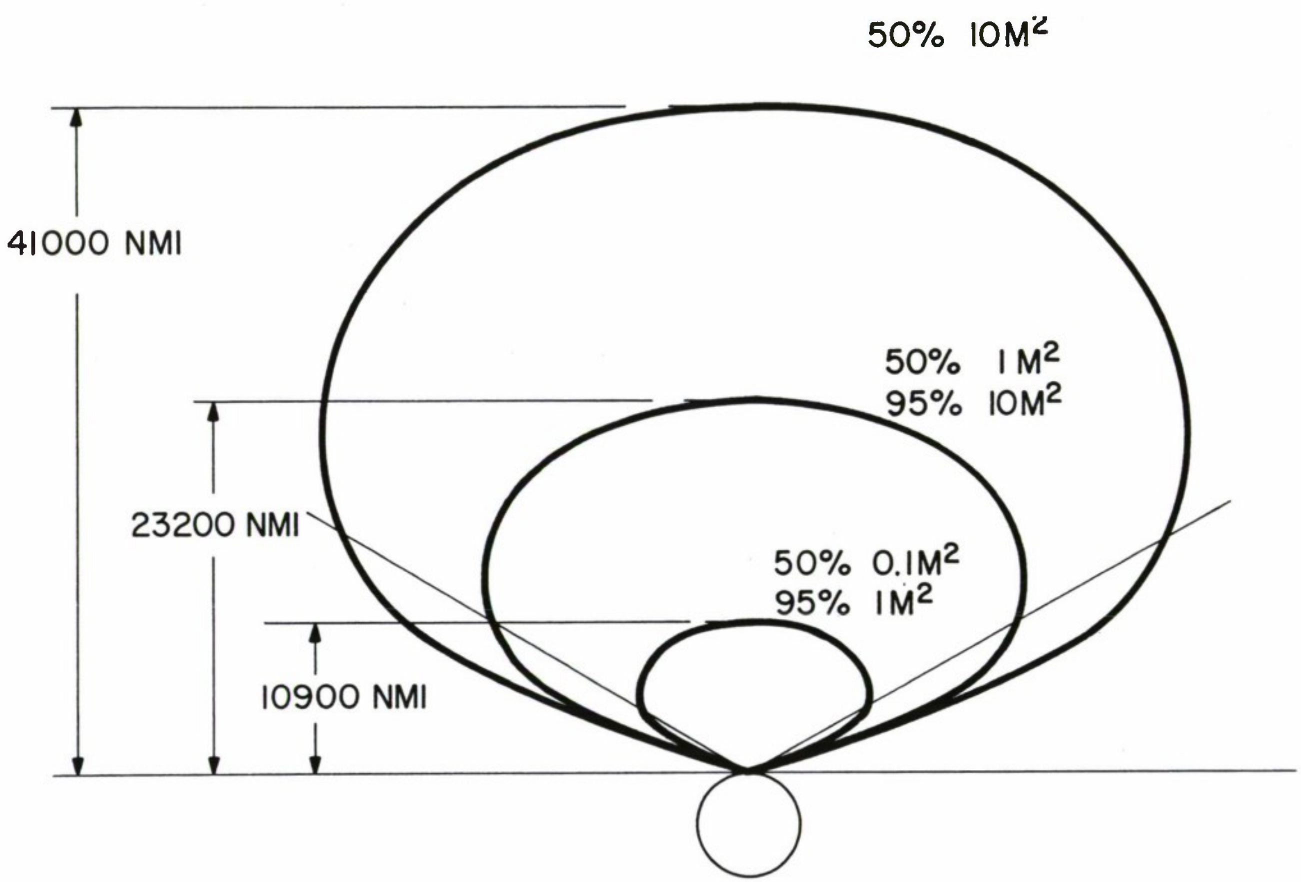

Fig. 9 - Geometry of system coverage

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Table 1

Evaluation of Detection System Parameters at 150 and 450 Mc/s

System Parameters	150 Mc/s	450 Mc/s	150 Mc/s
Beamwidth (interferometer antenna)	$0.072^{\circ} \times 120^{\circ}$	$0.024^{\circ} \times 120^{\circ}$	$0.072 \times 120^{\circ}$
Gain	4720	14,200	4720
Near Field	1600 stat mi	4800 mi	1600 stat mi
Beamwidth (Detection Antenna)	$0.072^{\circ} \times 15^{\circ}$	$0.024^{\circ} \times 15^{\circ}$	$0.072^{\circ} \times 15^{\circ}$
Gain	37,700	114,000	37,700
Beamwidth at 20,000 miles	25.2 mi	8.4 mi	25.2
Time in beam (at 4 mps)	6.2 sec	2.1 sec	6.2
Bandwidth needed	.2 cycles	.5 cycles	.2 cycles
Noise temperature	1000°K	250°K	1000°K
Predetection bandwidth (Detection)	100 cycles	300 cycles*	100 cycles
Sensitivity (13 db = S/N)	153 dbm	154 dbm	153 dbm
Sensitivity of phase meter	163 dbm	163 dbm	163 dbm
Gain of transmitting antenna	9,440	28,400	4720
Power	2×10^{6} watts	2×10^{6}	10^{6} watts
Range for $\sigma = 10$ ft^2 = 1 m^2 (Size used in calculation)	1.4×10^{8} feet	1.4×10^{8} feet	10^{8} feet
	26,700 stat mi (23,200 naut mi)	26,700 stat mi (23,200 naut mi)	19,000 stat mi (16,400 naut mi)
Range for $\sigma = 100$ ft^2 = 10 m^2 (Size used in calculation)	47,000 stat mi (41,000 naut mi)	47,000 stat mi (41,000 naut mi)	33,700 stat mi (29,000 naut mi)
Range for $\sigma = 1$ ft^2 = 0.1 m^2 (Size used in calculation)			
Bandwidth	0.4 cycle	1.0 cycle	0.4 cycle
Sensitivity	160 dbm	160 dbm	160 dbm
Range	12,600 stat mi (10,900 naut mi)	12,600 stat mi (10,900 naut mi)	9000 stat mi (7800 naut mi)

*Assumed bandwidth to keep the number of comb-preselector filters the same at 450 Mc/s as at 150 Mc/s.

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Angle Measurement

The antenna patterns determine the angle of arrival of the return signal to within 0.02° to 0.07° in one direction and to ±7.5° in the other. This angular resolution is increased by using several interferometer antennas. The sensitivity of the receivers in this angle measuring system, once the doppler slot is known, is 162 dbm. Thus,antennas may be used having gains 9 db less than were needed for the detection channel. Antennas employing only one lobe will be adequate for the angle measuring system. At 460 Mc measurements can be made to 0.1 mil accuracy with resolution to 0.02 mil; at 150 Mc the accuracy is 1 mil and the resolution is .06 mils.

Range Measurement

With the angle of arrival measured quite accurately by the interferometer, the range to the target is all that is needed to locate it. A ranging system using as much of the detection equipment as possible, but in no way limiting the detection range, is employed. It may be as nonambiguous as needed and as accurate as required

Consider a second transmitter generating a frequency removed 1 cps from the detection transmitter. The phase of the two transmitted signals is compared to the phase of the reflected signals. The phase of the reflected signals, as compared to the transmitted signals, will be a direct measure of the range to the target and will be nonambiguous to a distance of 83,000 nautical miles.

While this measurement will be nomambiguous, it also will not be very accurate. To improve the accuracy, another frequency separated by perhaps 5 cps from the detection signal will improve the accuracy by a factor of five. Other frequencies, say 25 cps, 125 cps, 625 cps, etc., may be used to further improve the accuracy. When the phases of all of these side tones are compared to the detection frequency, a range nonambiguous to 80,000 nautical miles and accurate to perhaps 0.10 miles is obtained.

Since the approximate frequencies of the side tones are known when the doppler of the detection device is determined, the power of each side tone need be only approximately 0.1 that of the detection device. The total power in the side tone will be approximately the same as in the detection transmitter.

Detection at Shorter Ranges

Detection at closer ranges is, of course, much easier than at 30,000 miles. Portions of the long-range receiving antennas can be used for measurements down to ranges of 85 nautical miles. However, at shorter ranges additional requirements are imposed in order to provide adequate orbit prediction.

Orbit Prediction

In general, orbit predictions can be obtained in two ways. One method involves measurement of position and time at two widely separated points in the orbit. The fan-type system is especially adaptable for this measurement. Lower satellites, on which only one observation can be made, require a different technique, that of measuring position and velocity.

Consider now that the orbit of a satellite is to be predicted using a velocity measurement. The velocity V may be expressed as follows:

$$V^2 = V_r{}^2 + V_t{}^2 = \mu \left(\frac{2}{r} - \frac{1}{a}\right) ,$$

where V_r and V_t are the radial and tangential components of velocity, r is the distance from the center of the earth, a is the semimajor axis of the orbit, and $\mu = g\, R_o^2$. One obtains

$$da = 2a^2 \left(\frac{dr}{r^2} + \frac{V_r\, dV_r + V_t\, dV_t}{\mu}\right) .$$

For simplicity, consider the period as the desired parameter. Since

$$T^2 = \left(\frac{2\pi}{\mu}\right)^2 a^3$$

$$dT = \frac{3}{2}\frac{T}{a}\; da = 3aT \left(\frac{dr}{r^2} + \frac{V_r\, dV_r + V_t\, dV_t}{\mu}\right) .$$

'or a circular orbit, $a = r$, $\mu = av^2$, $dr = o$ and $V_r = o$. Therefore,

$$\frac{dT}{T} \sim 3\; \frac{dV_t}{V_t}$$

ut $dV_t/V_t = d\theta/\theta$ where $d\theta$ is the resolution of the receiving system and θ the eamwidth.

For optimized detection, antenna beamwidths of approximately 0.1° (0.002^r) ppear desirable. At 150 Mc/s an angular accuracy of 0.001^r and a resolution of $.0001^r$ appear reasonable with interferometer baselines of about 1 mile. Under hese conditions,

$$\frac{dT}{T} = 3 \left(\frac{0.0001}{.002}\right) = 0.15.$$

ne period can thereby be measured to 15 percent.

Increased Accuracy

To improve the accuracy, a higher frequency could be transmitted simultaneously with the detection frequency. The doppler experienced by this higher frequency is related to the doppler at the detection frequency by the ratio of the frequencies. Once the detection frequency is known, the doppler of the higher frequency is known and phase-measuring receivers can be tuned to receive it.

Consider now that an angular rate frequency of 1500 Mc/s is selected. To have a 0.1° beam, this antenna need only be 0.1 mile long. The far field will start at 160 miles. In the 150 Mc/s antenna the far field starts at 1600 miles. The beam-width of this antenna is never less than 1 mile, so an additional measurement time for the high-frequency signal can be obtained by using two 0.1-mile antennas located at either end of the 1-mile antenna to give an effective observation angle of 1/100 or 0.01^{r} at 100 miles and 0.005 at 200 miles. Assuming a one-mile baseline, the resolution of the high-frequency antenna will be 10^{-5} radians, giving the following values for $\frac{dT}{T}$.

Height:	100 miles	200 miles	300 miles
$3\,\frac{d\Theta}{\Theta} = \frac{dT}{T}$	.003	.006	.009
Accuracy of 100-minute orbit	18 sec	36 sec	48 sec

The determination of orbits by making observations of position at two separated points in the orbit can be considered as a special case of the $d\Theta/\Theta$ criterion in the following manner. In Fig. 10 consider that observations are made from A and B with an accuracy of dX (A and B are separated by a central angle Θ). Let r_A and r_B be the radius vectors of the observations. Then dx_1/r_A is the angular error in the observation at A, and dx_1/r_B is the angular error in the observation at B. If we assume $dx_1/r_A = dx_2/r_B$, then $d\Theta_r = dx_1/r_A = dx_2/r_B$. $d\Theta_r$ is related to the accuracy of observation at A and B by the relationship $d\Theta_A = dx_1/H_A$. From the figure,

$$d\Theta_A = \frac{d\Theta_r\,(H_A + R)}{H_A} ,$$

$$d\Theta_r = \frac{H_A\,d\Theta_A}{H_A + R} .$$

Therefore,

$$\frac{dT}{T} \sim 3\,\frac{d\Theta_r}{\Theta} = \frac{3\,d\Theta_A}{\Theta}\left(\frac{H_A}{H_A + R}\right) .$$

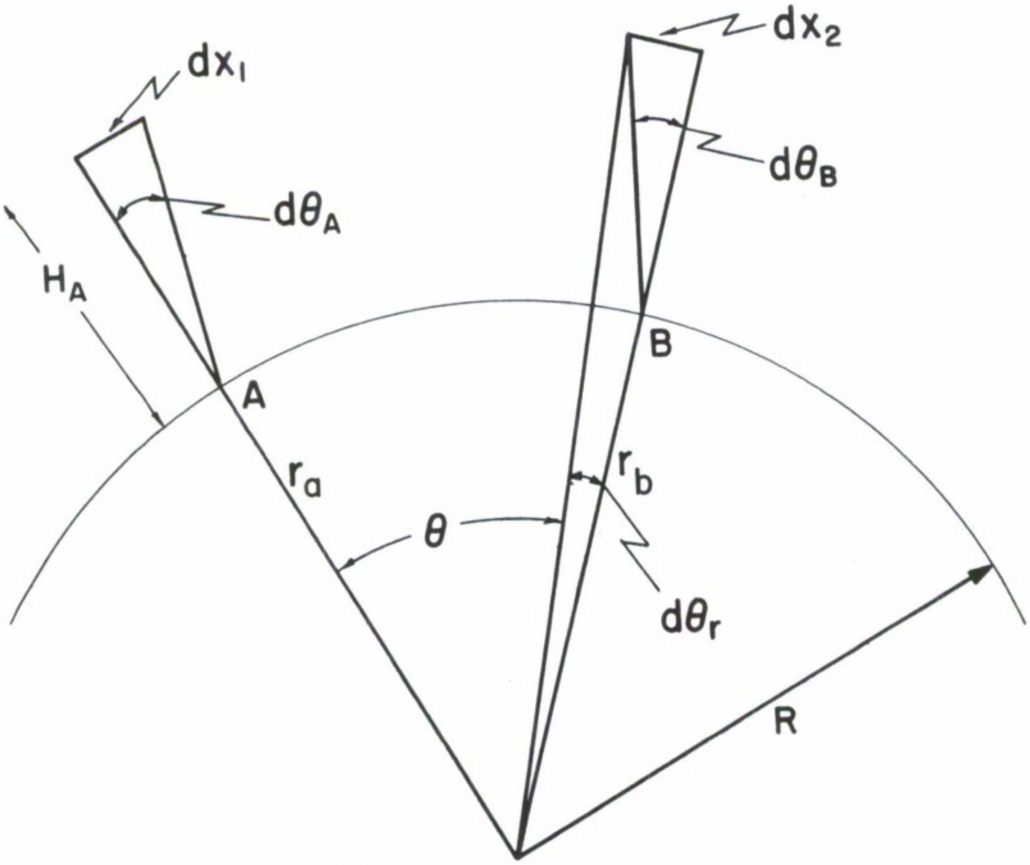

Fig. 10 - Geometry of the two-fence velocity determination

This equation shows that observations made at low altitudes provide better orbit determinations than at high altitudes by the ratio of the altitude to the radius vector. At great distances ($H_A > R$) this equation reduces to $dT/T = 3\ d\theta_A/\theta$.

In two station installations of this type it might be expected that A and B would differ in central angle by perhaps 0.1r. At 150 Mc/s $d\theta_A \gtrsim 10^{-3}r$; at 450 Mc/s $d\theta_A = 10^{-4}r$.

For $\theta = 0.1^r$:

H_A	1000 miles		30,000 s miles	
	150 Mc/s	450 Mc/s	150 Mc/s	450 Mc/s
$d\theta$	0.0001^r	0.0001^r	0.001^r	0.0001^r
dT/T	0.006	0.0006	0.026	0.0026

Improved accuracy will be obtained by either having stations spaced at greater central angles or by using more accurate observations. All calculations assume $\frac{dr}{r} < \frac{d\theta}{\theta}$. Since dr can easily be made of the order of 0.1 mile, $dr/r = 2 \times 10^{-5}$.

This same technique can be used to compare tracking devices with fixed stations. Consider a device that tracks a satellite over 90° of angle with an accuracy of 0.1°. Then $d\theta/\theta = 0.1/90 = 0.001$ for $dT/T = 0.003$.

Low-Height Coverage

To complete an installation, giving coverage down to the horizon, two low-angle installations are necessary. The beamwidths on these installations are 30° x 0.07°. The reduced fan width permits a power reduction by a factor of four (to 250 kw). The range required at these angles is less, so the power can be further reduced. 100 kw has been selected for the detection transmitter and 100 kw for the total ranging power. Due to the necessity for measuring at low elevation angles a frequency of 450 Mc/s has been selected. Phased arrays will be used to obtain the low-angle coverage. A range of 2000 miles on a 0.1 m^2 target (50 percent probability), or 95 percent probability on a 1 m^2 target at the same range, will be obtained.

Site Selection

The problem of site selection is that of finding islands separated properly to minimize feedthrough and large enough for proper antenna installations. The first installation should be such as to (a) minimize time between launch and detection, (b) provide coverage on low-inclination satellites, and (c) cover satellites to extreme ranges.

To meet condition (a), the installation should be approximately 90° from the present installation in the U.S. In the Pacific, this places the station in the region of 150° to 180°E.

Of the U.S.-controlled islands in the region only Ponape is large enough for a receiver installation (but is not large enough to provide the required separation between transmitter and receiver). Truk-Ponape covers a line within 7° of the equator and will intercept early standard Russian-satellite passes.

The criterion used for site selection of a new station is that the site should fit into a plan to provide eventual first-pass detection of all low-period and 24-hour-period satellites. An installation on or near the equator approximately 90° in longitude from the U.S., having a range capability of approximately 30,000 miles, will provide (a) early detection, (b) equatorial coverage, and (c) :overage on 24-hour satellites.

'requency of Operation

While the general requirements of a space surveillance system are relatively ioncontroversial, some of the details are subject to question. One such problem .s that of frequency of operation. The problem is complicated by several factors. .t the higher frequencies, observations can be made with much greater accuracy .nd less trouble from electron clouds. At the lower frequencies the accuracy is .ess. The cost and time required to perform a given task are also significantly .ower.

At the lower frequencies (below 200 Mc/s) the system noise figure is limited y sky noise. At the higher frequencies (450 Mc/s) it is determined by receiver oise. For calculations of receiver sensitivity, a system temperature of 1000°K as been assumed for the 150 Mc/s case and 250°K has been assumed for the 450 Mc/s ase. Due to the difficulties in obtaining better noise figures economically, ıd due to antenna cabling losses at higher frequencies, the system temperature ɔuld remain at about 250°K.

Absorptive coatings are effective in reducing the detection range of devices ɜspecially mono-static) operating at high frequencies. At lower frequencies ıere the wavelength is large compared to the size of the reflecting object ab- ›rptive coatings are ineffective.

On the other hand electron clouds are more easily seen at the lower fre- ıencies. However, blackouts due to bursts would not appear to be serious at ·equencies of 150 Mc or above. A burst, to be effective, would have to be curately positioned close to the detection device and would be effective for time duration of minutes. If an enemy were to fire a device for the purpose of acking out reception temporarily he might better attempt to hit the detection device d thereby black it out altogether.

Feedthrough

The principal problem with a high-performance cw system is that of feedthrough. The present Naval Space Surveillance System is a tristatic system having stations spaced far enough apart to utilize the attenuation due to the scatter link. In the scatter region the radiation reduction for every doubling of the distance is approximately 26 db, 20 db more than in the square-law region

One of the reasons that the present system operates so well is that it is being used to detect high objects. For this requirement the receivers must be placed a long distance apart to give a reasonable triangulation cut. At this distance the feedthrough is small. To use such a system on islands, three islands would have to be located on a great circle.

By using a receiving station having a ranging capability, only two island installations need be made. If a single island is large enough, then both installations can be made on it. This discussion is aimed at finding the minimum size of an island large enough for both installations.

The power ratio between transmitter and receiver level will be calculated first. The transmitter operates at +60 dbw. The receiver at about -185 dbw for a total excursion of 245 db. Antenna gains at 150 Mc/s are approximately 40 and 50 db. With care, the low-elevation-angle radiation can be kept down perhaps 45 db on each antenna.

By using an antenna looking for signals at low-elevation angles, a signal can be introduced to the receivers to cancel the low-elevation signal received by the vertically looking antennas. This technique will reduce the feedthrough by 30 db.

Filters in the receiver will reduce the feedthrough by 50 to 80 db. From these three effects the coupling can be reduced by 245 db to 165 to 135 db. The difference between the two figures is due to the care required to obtain the 80-db figure. Much better filters must be used to obtain 80 db.

Figure 11 shows the attenuation due to scatter and due to separation. Figure 12 shows a graph of the combined effects. From Fig. 12 it is apparent that for the 135-db isolation figure a minimum distance of 35 miles is required, while for the 165-db figure a separation of 90 miles is indicated.

It should be recognized that a considerable separation between transmitter and receiver has an advantage with respect to detecting an object coated to minimize reflection. While the reflection at zero angle of incidence can be made small, the reflection at large angles of incidence remains considerably larger.

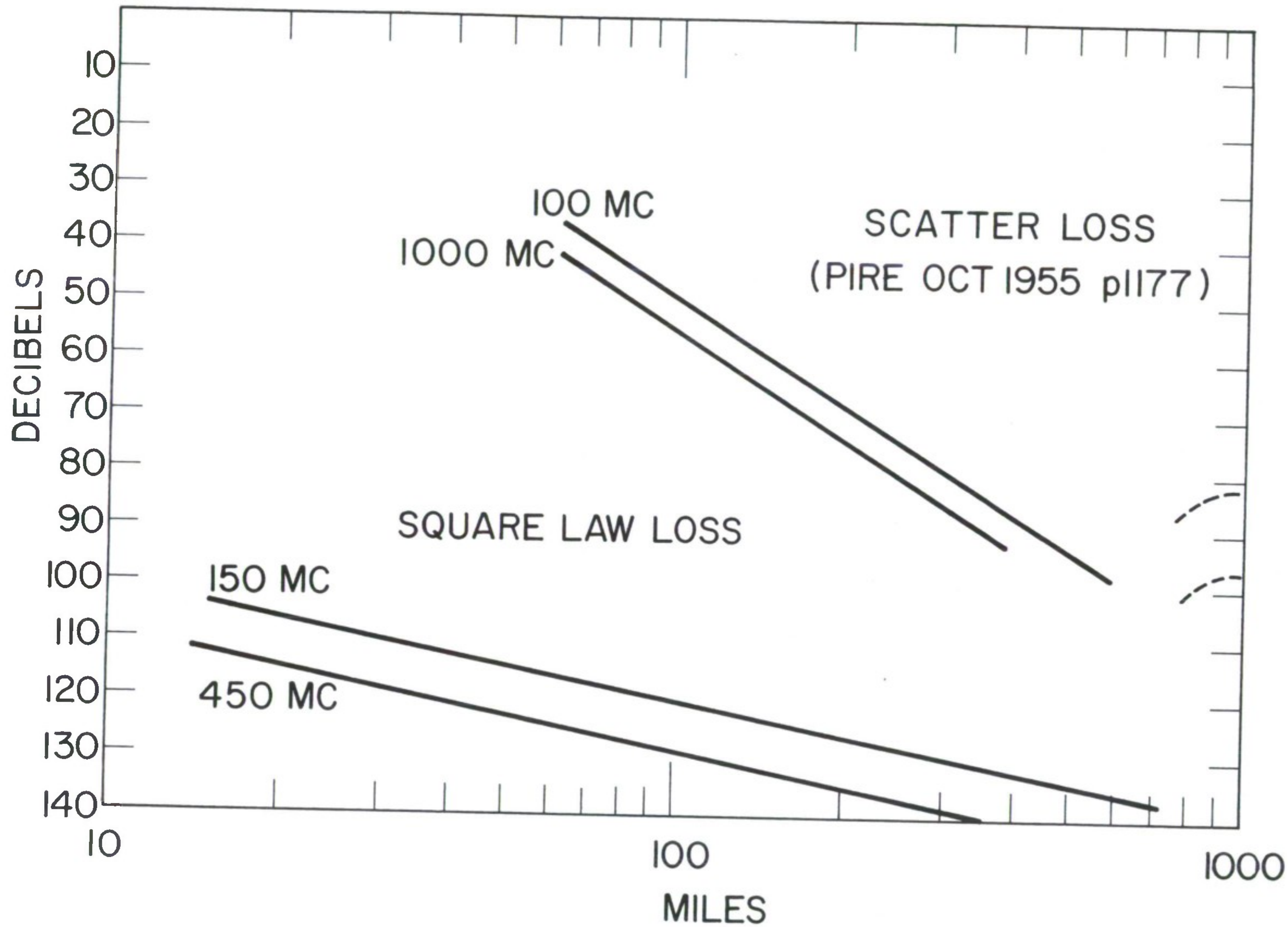

Fig. 11 - Isolation due to scatter and separation (square law)

[redacted]

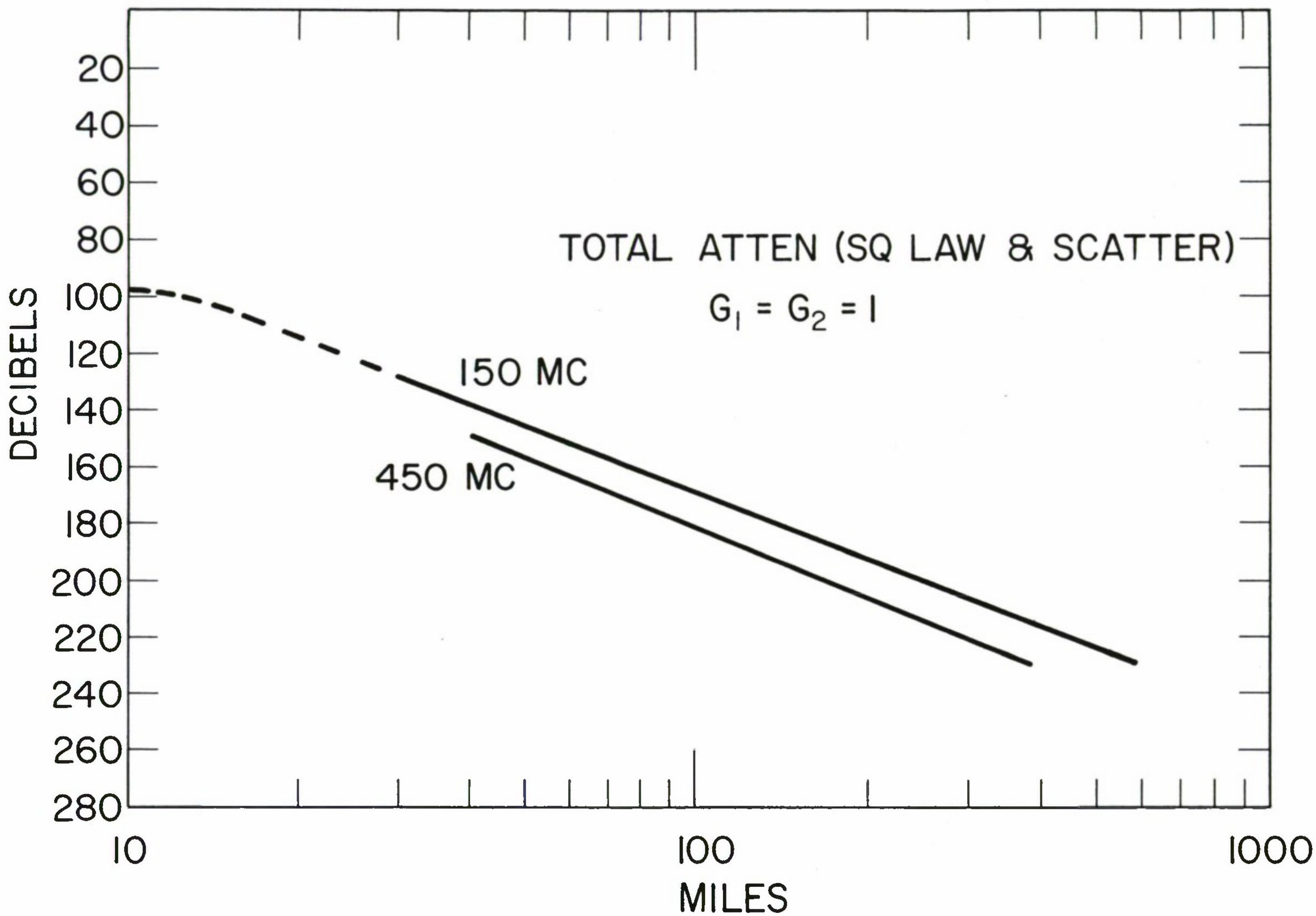

Fig. 12 - Isolator due to combined scatter and square law terms

[redacted]

If the effective size of an object is decreased by a factor of 4000 by means of absorptive material a system designed for a detection range of 30,000 miles will have its range reduced by a factor of about 10.

Saturation

One of the advantages of a detection system that uses a thin-fan beam is that the signal stays in the beam for only a short time. The system then has much time during which it can detect other objects. For instance, in the present Naval Space Surveillance System the average time used in a satellite observation is approximately one second. At each receiving site an observation on a single satellite will occur perhaps twice per day. The time used per satellite then is two seconds. A maximum of approximately 40,000 objects could be tracked.

Under these conditions it is very unlikely that two objects will appear in the system simultaneously. In the event they do, the system will chose one and will not be confused unless the two objects appear in the same doppler slot. Since 160 slots exist, this possibility is unlikely. By having a phase meter associated with each doppler slot a maximum of 6,400,000 objects could be observed. Since this is a much larger number than is expected, a much more modest number of phase meters can be used.

Since it may be expected that the moon will be detected for a considerable duration of time, it is desirable that a minimum of two satellites be measured simultaneously. The use of three sets of phase meters allows a maximum of 120,000 objects before saturation occurs. Ten thousand objects can be handled with a safety factor of 12.

COST AND TIME SCALE

The costs of various systems are given in the table below. Transmitter costs are based on the cost of the Lake Kickapoo site, with appropriate adjustments. Receiver costs are based on the costs of present stations, again with appropriate adjustments.

The costs are based on a system capable of detecting objects to 30,000 miles. This cost is suitable for detecting 24-hour satellites. For satellites at lower heights the small 1-mw stations can be used, at reduced cost. The prorated cost of operating a U.S.-based system is estimated as 1.1 million; the cost of operating overseas is estimated as 3.0 million, annually.

The time scale is based on the experience gained in building the present system. A transmitter site takes approximately one year to build. Comb filters take about the same amount of time. Antennas and other items can be completed more rapidly. Since the routine contracting process requires 6 months, a 150-Mc/s installation could be completed in the U.S. in 18 months. For overseas, six months of additional time should be programmed. For the 450-Mc/s system, an additional four months should be programmed.

[redacted]

Table 2

Cost of System

Items	500 kw Lake Kickapoo 1 mi antenna	2 mw 150 Mc/s U.S.	Island	2 mw 450 Mc/ U.S. 2 mi antenna
		2 mi antenna		
Detection Transmitter	1.25	5.50	5.75	6.50
Detection Antenna	0.375	1.50	1.75	1.75
Ranging Transmitter	none	6.00	6.25	6.75
Ranging Antenna	none	2.50	2.75	3.00
Public Works	0.375	1.25	2.75	1.25
Power Station	0.000	0.00	1.75	0.00
Support Engineering	0.25	0.35	0.45	0.45
Subtotal	2.25	17.10	21.45	19.70
Detection Array (1 mi antenna)		2.0	2.25	2.75
Interferometer		2.2	2.50	2.50
Comb Filter		1.6	1.70	2.00
Phase Electronics		0.4	0.50	0.50
Ranging Electronics		0.4	0.50	0.50
Public Works		0.5	2.50	0.50
Support Engineering		1.0	1.50	1.50
Subtotal		8.1	11.45	10.25
TOTAL		25.20	32.90	29.95
Low Angle Coverage Complete 100 kw at 450 Mc (2 looks)		7.7	7.7	7.7
GRAND TOTAL		32.9	40.60	37.65

[redacted]

Time Scale:

U.S.: 150 Mc/s - 18 months
Island: 150 Mc/s - 24 months
U.S.: 450 Mc/s - 22 months
Island: 450 Mc/s - 28 months.

The total cost of R and D, procurement and installation to provide a complete system with a range to 30,000 miles and low height coverage to 85 nautical miles over a span of 1500 miles is 32.9 million if constructed in the U.S. Yearly operating costs of 1.1 million assume integration with the present system. The increased cost for operations overseas assume independent data processing and computational capability. This initial unit would be compatible with possible future extensions and growth requirements in that high precision angle measurements could be added and traffic capacity increased as might be required.